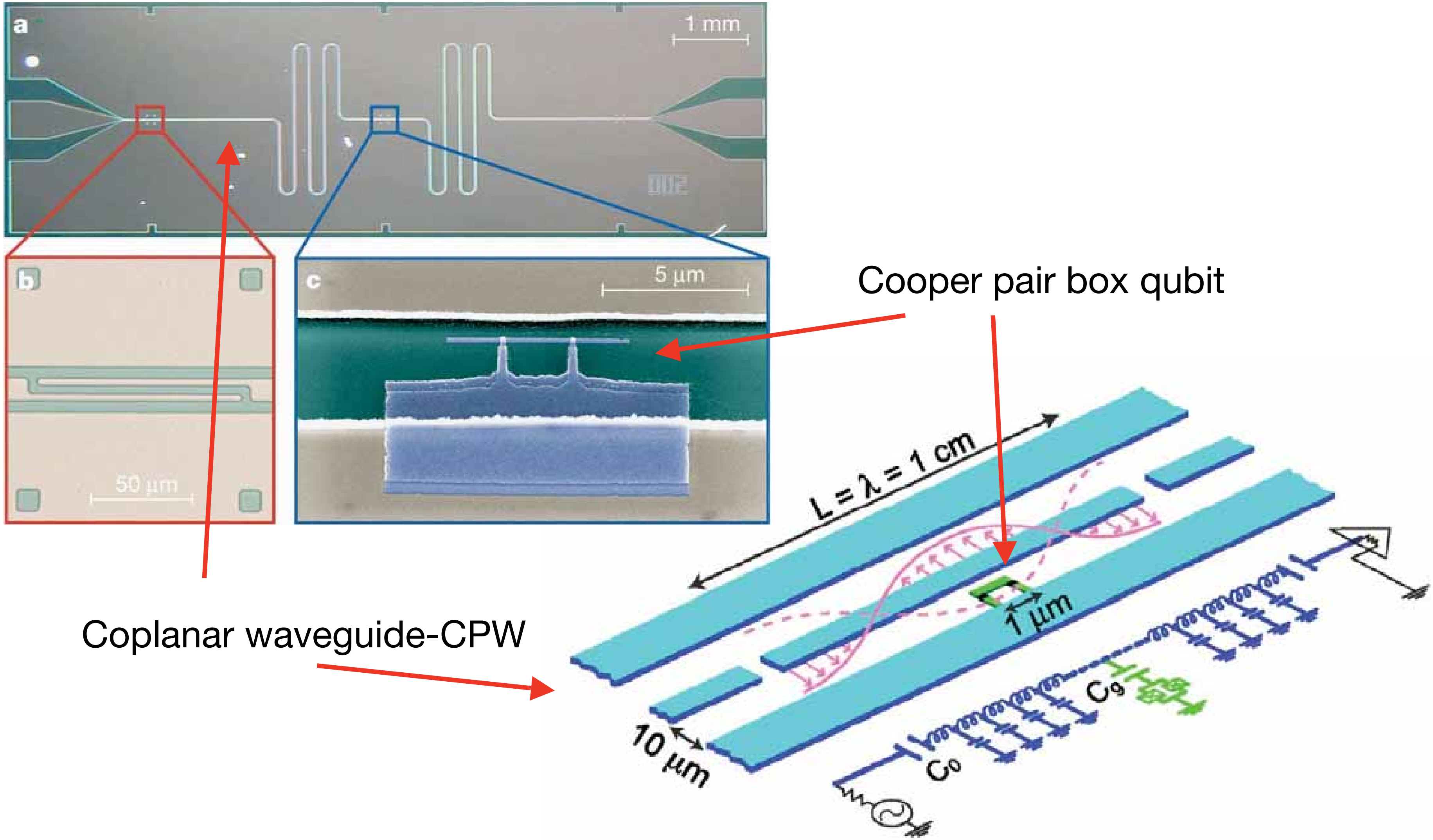
In the first lecture, we learned about circuit QED applied to quantum computing

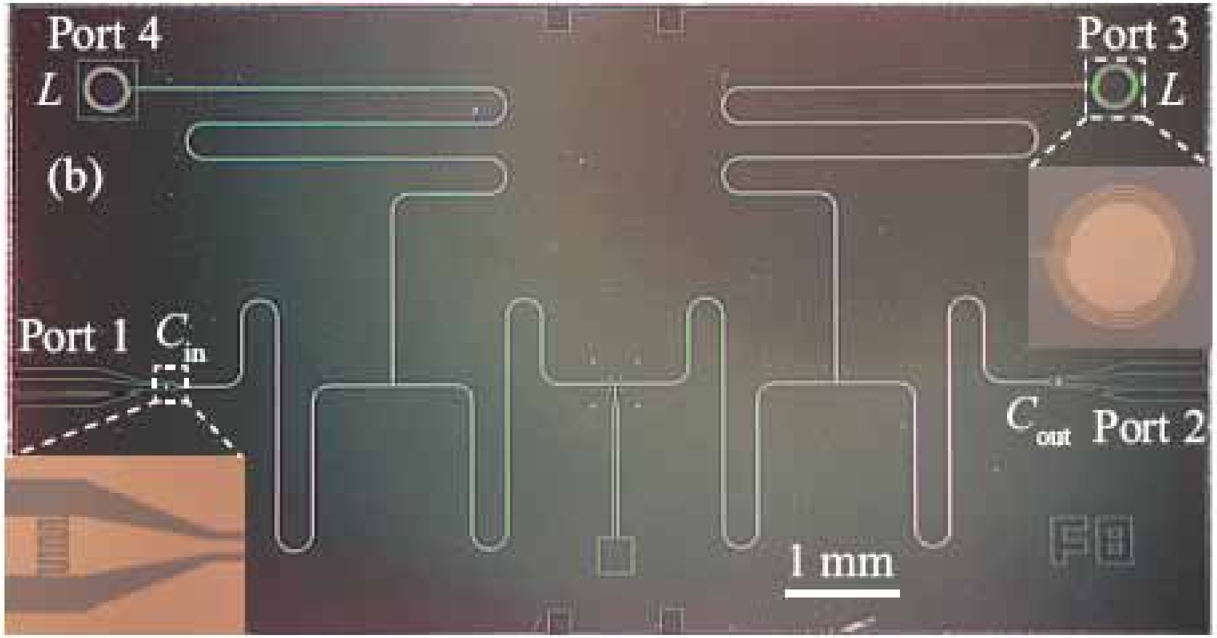


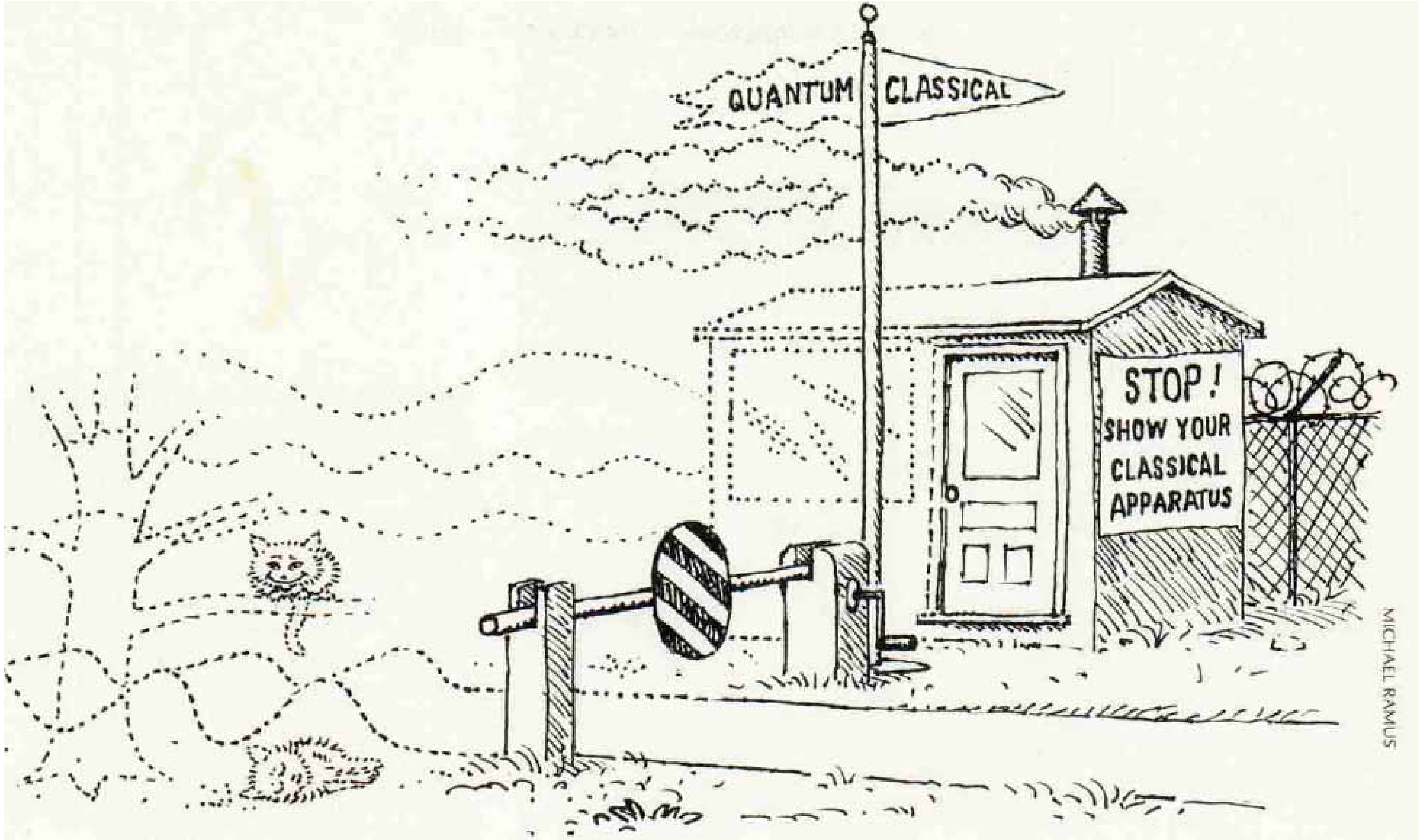
[A. Wallraff *et al.*, *Nature* **431**, 162 (2004);A. Blais *et al.*, *Phys. Rev.* A **69**, 062320 (2004)]

Often a technology developed for one particular application can find other unexpected applications

In the next two lectures, will give two examples of other applications of circuit QED

II. cQED and the Quantum-Classical Correspondence





“Determining the border between the quantum world ruled by the Schrödinger equation and the classical world ruled by Newton’s laws is one of the unresolved problems of physics.”

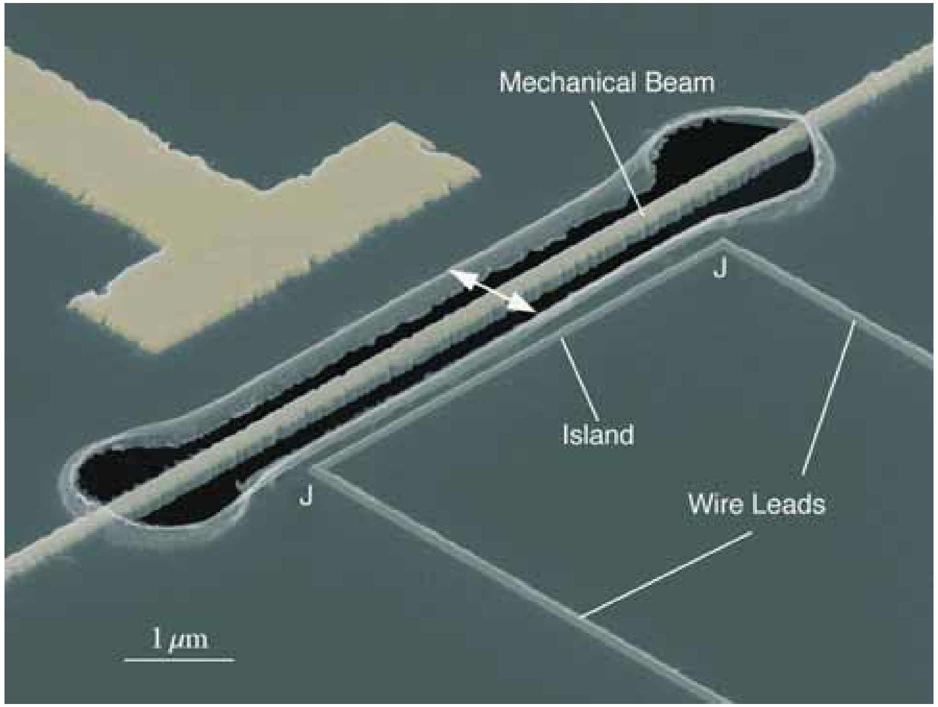
[W.H. Zurek, Physics Today, October 1991, p. 39]

Wish to prepare a mesoscale mechanical resonator in a quantum superposition state and then watch it become classical.

Few tens of mK

$$\hbar\omega \lesssim k_B T$$

Mechanical frequency: few tens of MHz



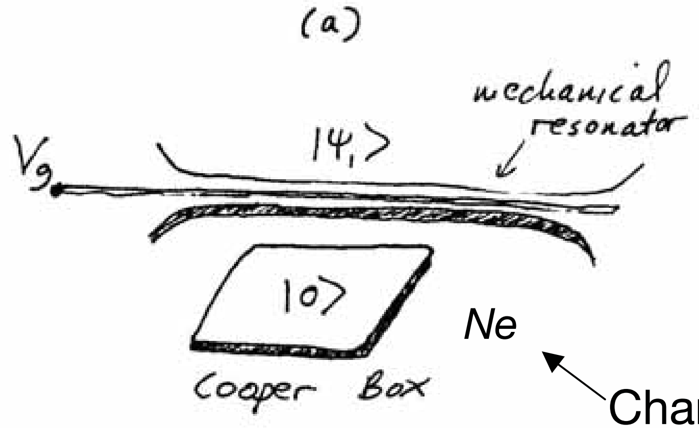
[M.D. LaHaye *et al.*, Science **304**, 74 (2004)]

Environmental decoherence at mK temperatures: two level systems, phonon radiation into supports,….

Use superconducting qubit to drive and probe mechanical resonator in a superposition state

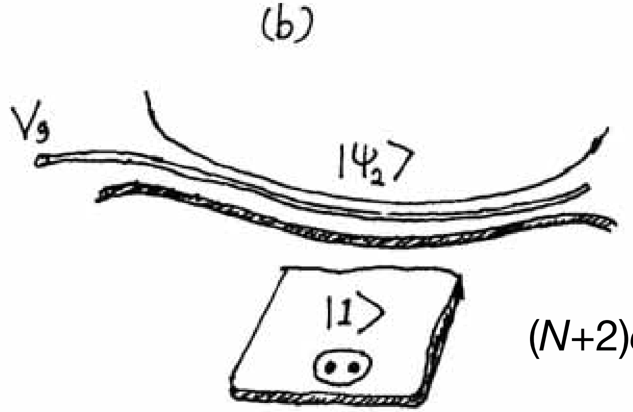
[A.D. Armour, M.P.B. & K.C. Schwab, PRL **88**, 148301 (2002)]

Gate voltage: coupled Cooper box qubit to mechanical resonator via electrostatic force



Ne

Charge on Cooper box



(*N*+2)*e*

$$(\alpha|0\rangle + \beta|1\rangle)\,|\Psi_1\rangle \rightarrow \alpha|0\rangle|\Psi_1\rangle + \beta|1\rangle|\Psi_2\rangle$$

But charge basis states strongly affected by environment noise.
Instead use charge degenerate basis states:
[E. Buks and M.P.B., PRB **74**,174504 (2006)]

$$|\pm\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle \pm |1\rangle\right)$$

Resulting (dispersive) qubit-mechanical resonator Hamiltonian:

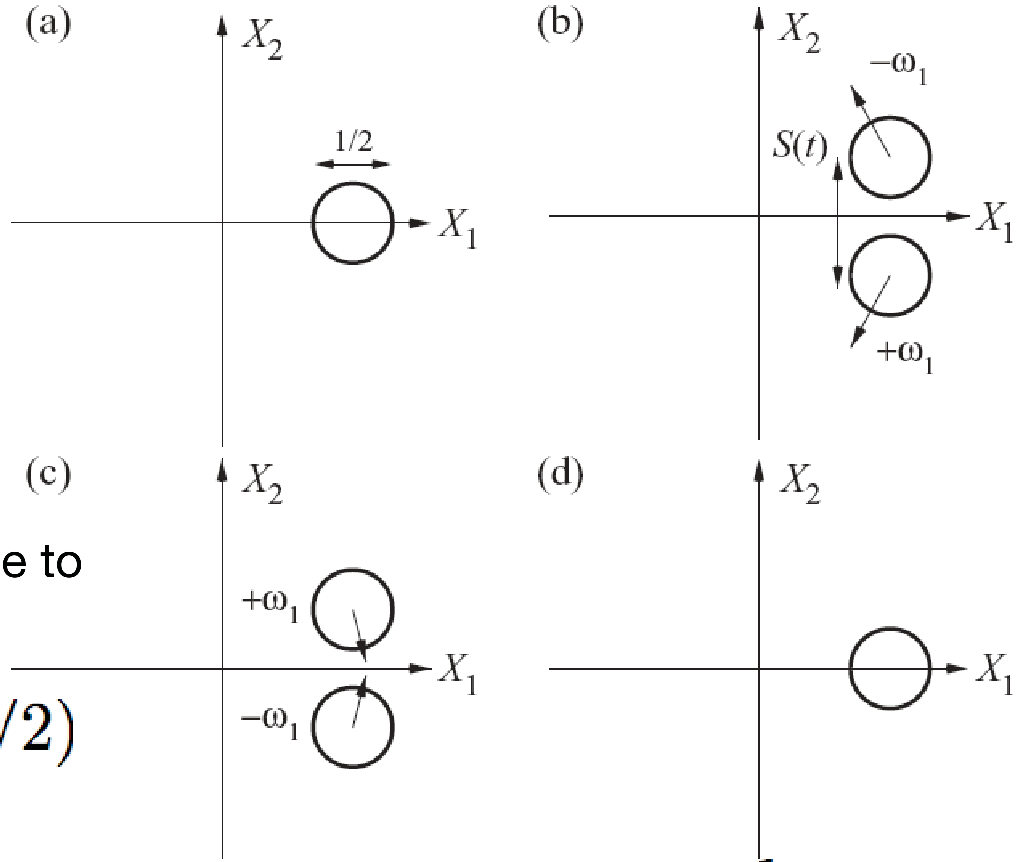
$$H = \Delta\sigma_z + \hbar\omega_1\sigma_z a^\dagger a + \hbar\omega a^\dagger a$$

Qubit Coupling Mechanical Resonator

Qubit basis states shift oscillator frequency

Evolution of mechanical resonator assuming coherent state and no decoherence (for simplicity)

$$\frac{1}{\sqrt{2}}(|-\rangle + |+\rangle)|\alpha_0\rangle \longrightarrow \frac{1}{\sqrt{2}}(|-\rangle|\alpha_-(t)\rangle + |+\rangle|\alpha_+(t)\rangle)$$



Apply a π-pulse to qubit at time t

$$\exp(-i\pi\sigma_x/2)$$

$$t_{\text{final}} = 2t$$

Get recoherence

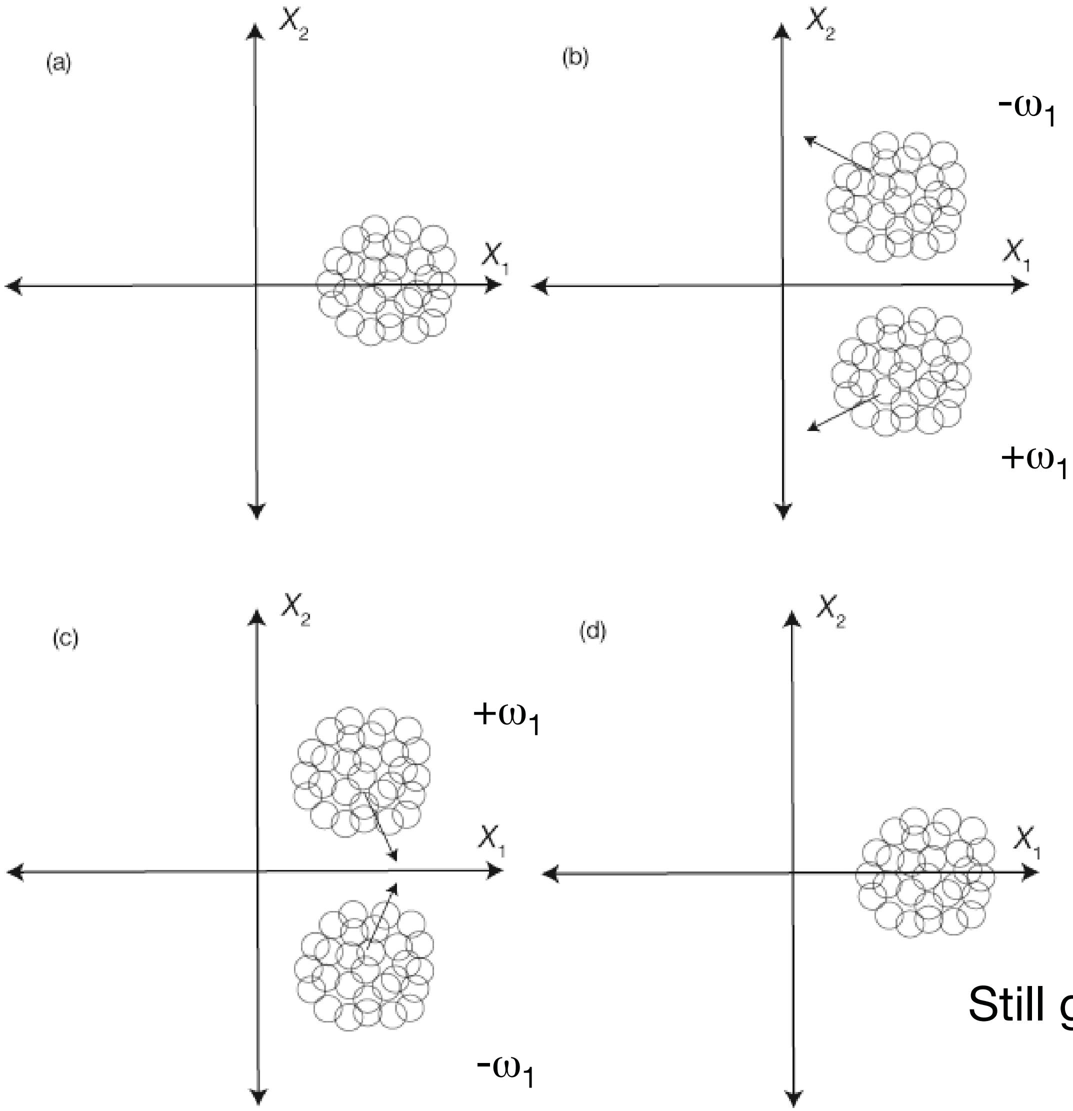
$$\frac{1}{\sqrt{2}}(|+\rangle|\alpha_-(t)\rangle - |-\rangle|\alpha_+(t)\rangle) \longrightarrow \frac{1}{\sqrt{2}}(|-\rangle + |+\rangle)|\alpha_0\rangle$$

Evolution of mechanical resonator initially in displaced thermal state

Initial qubit state:

$$\frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)$$

Apply a π-pulse to qubit at time t



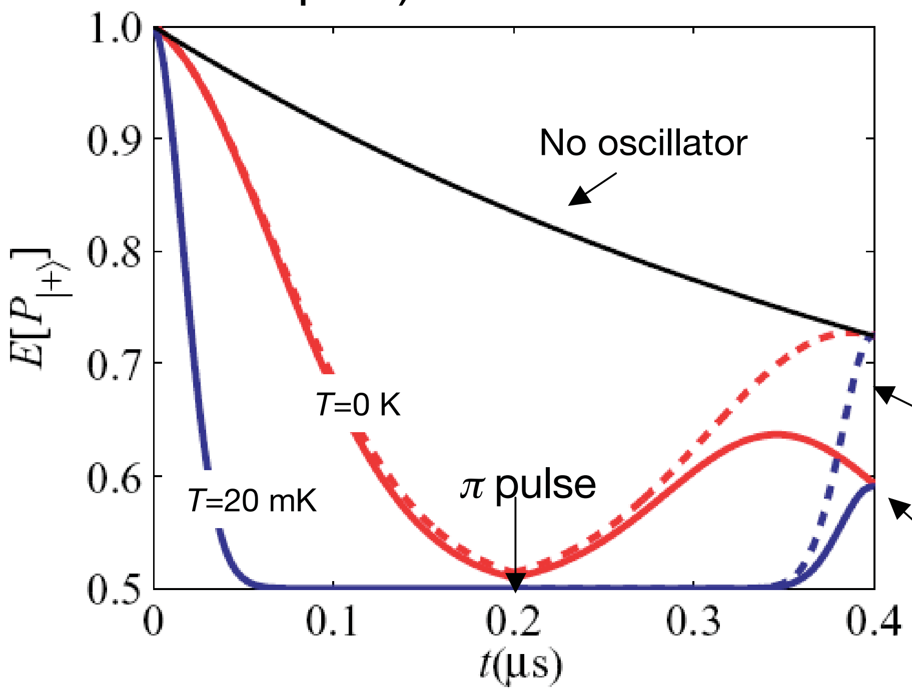
$$t_{\text{final}} = 2t$$

Still get recoherence!

What might we observe in an actual experiment?

$\omega/2\pi$	$=$	50 MHz	Mechanical frequency
$2\Delta/h$	$=$	5 GHz	Qubit energy
T_2	$=$	$0.5\ \mu$s	Qubit coherence lifetime
T	$=$	20 mK	System temperature

Probability of qubit to be in $|+\rangle$ state vs time (with initial and final $\pi/2$ rotations on qubit)



Oscillator without dissipation (dashed curves)

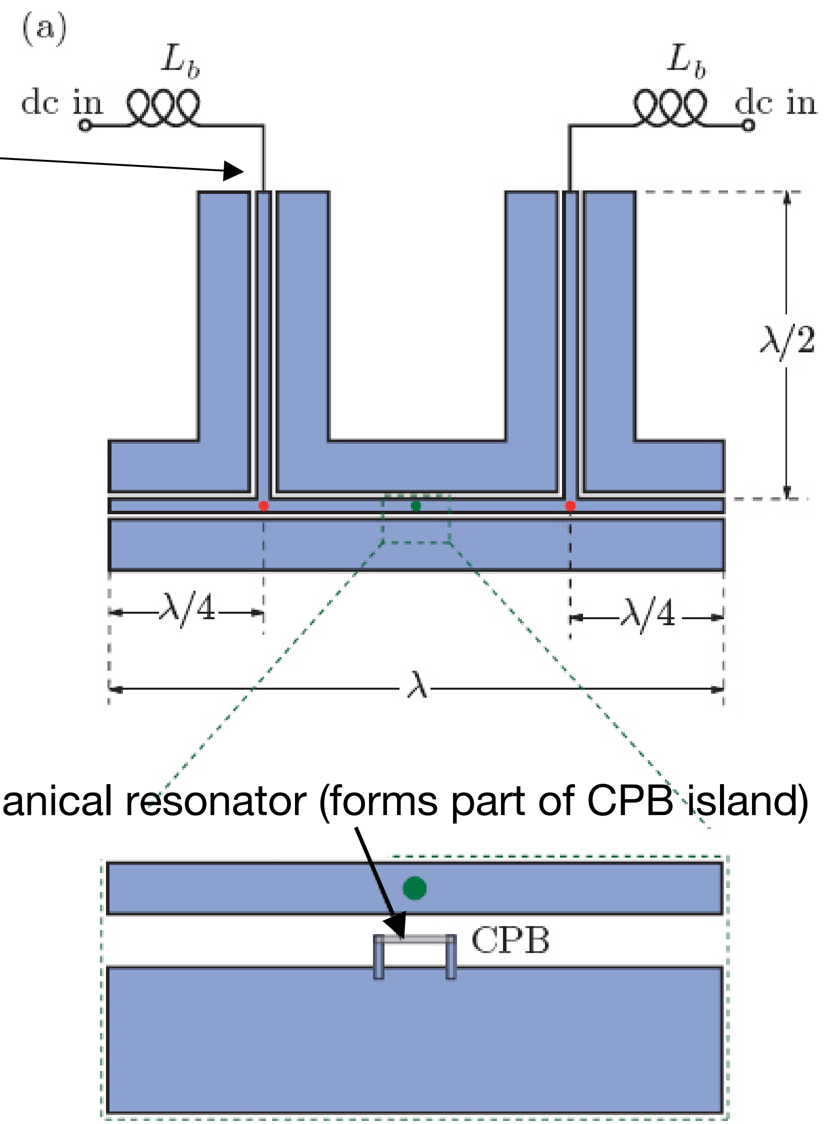
Oscillator with dissipation (solid curves): quality factor Q=3000

[A.D. Armour and M.P.B, New J. Phys. **10**, 095004 (2008); M.P.B. and A.D. Armour, New J. Phys. **10**, 095005 (2008)]

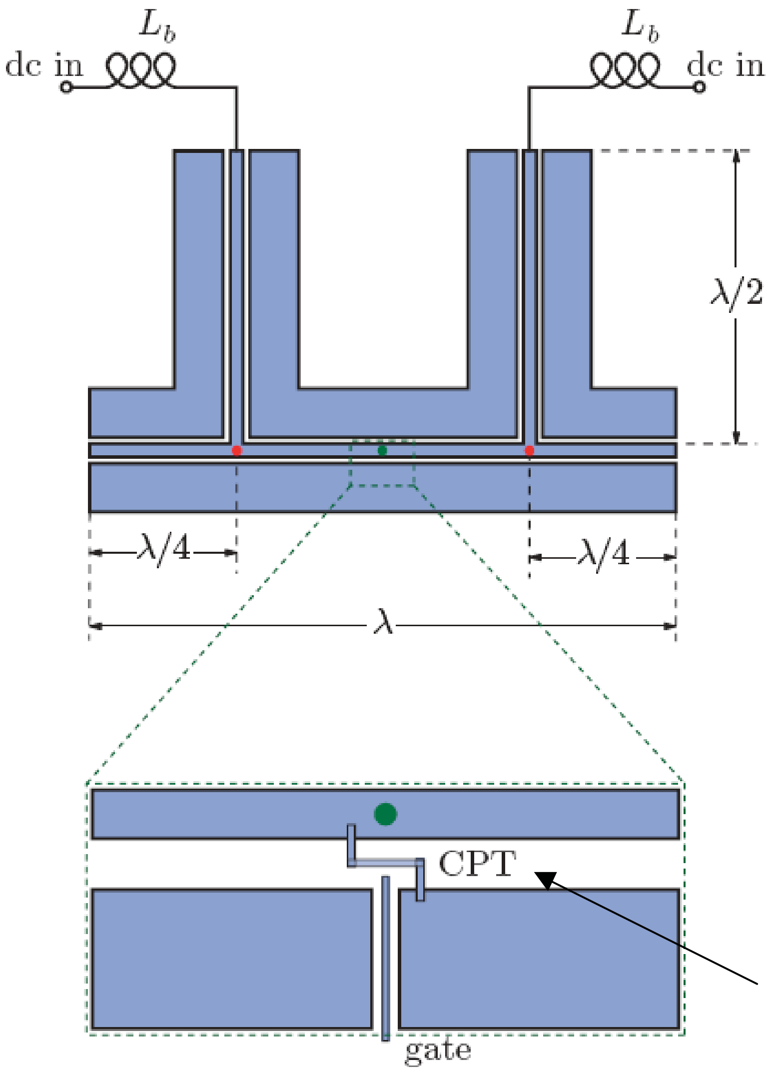
Coplanar waveguide-based realization of scheme

Centre conductor dc bias: necessary for

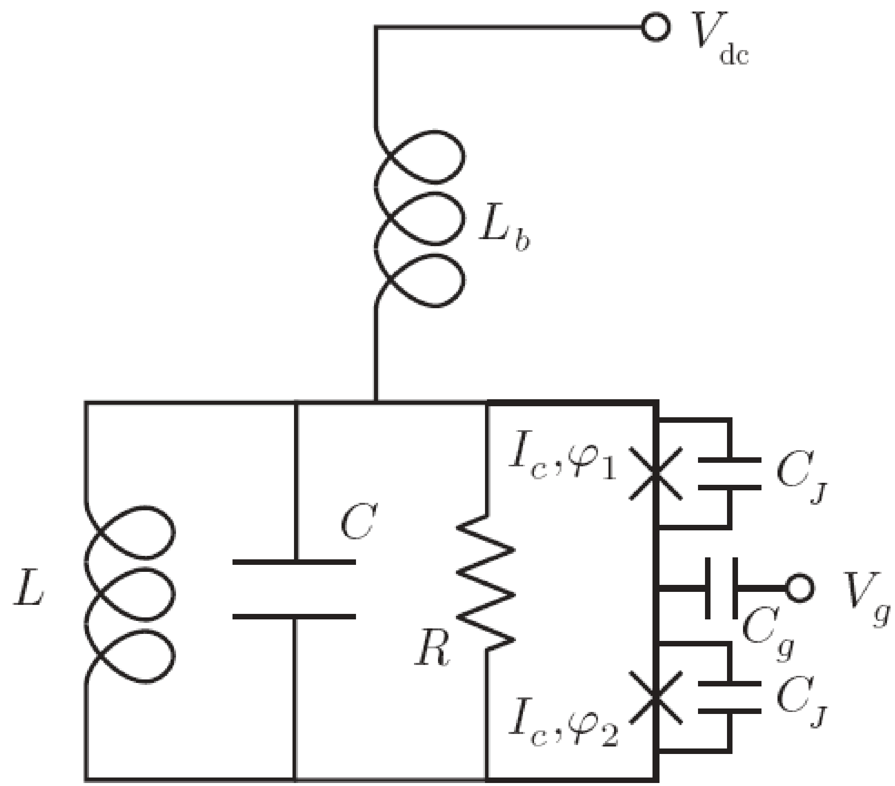
- Strongly coupling Cooper pair box (CPB) to mechanical resonator
- MHz ac driving of mechanical resonator→displaced thermal state



“Warm-up” investigation: quantum versus classical dynamics of a strongly nonlinear, low noise cavity-Cooper pair transistor system (no mechanical resonator)



Cooper pair transistor (CPT)



Single microwave mode equivalent circuit

Mechanical equivalent: oscillator-driven pendulum system

$$\gamma_\pm = (\varphi_1 \pm \varphi_2)/2$$

$$\mathcal{H} = \frac{p_+^2}{2M_+} + \frac{1}{2}M_+\omega_+^2\gamma_+^2 + \frac{p_-^2}{2M_-} + M_-\omega_-^2 \cos\gamma_- \cos(\gamma_+ + \omega_d t)$$

$$\omega_d = \frac{L}{L_b}\frac{eV_{dc}}{\hbar}$$

$$\frac{M_+}{M_-} = \frac{R_K}{Z}\frac{E_{C_J}}{\hbar\omega_0} = \frac{2C}{C_J} \gg 1 \qquad \frac{\omega_-}{\omega_+} = 2\frac{\sqrt{E_J E_{C_J}}}{\hbar\omega_0} \gg 1$$

Have slow, massive oscillator (cavity mode: phase coord. γ_+) interacting with fast, low mass pendulum (CPT: phase γ_-, charge $N = -p_-/\hbar$ coords.).

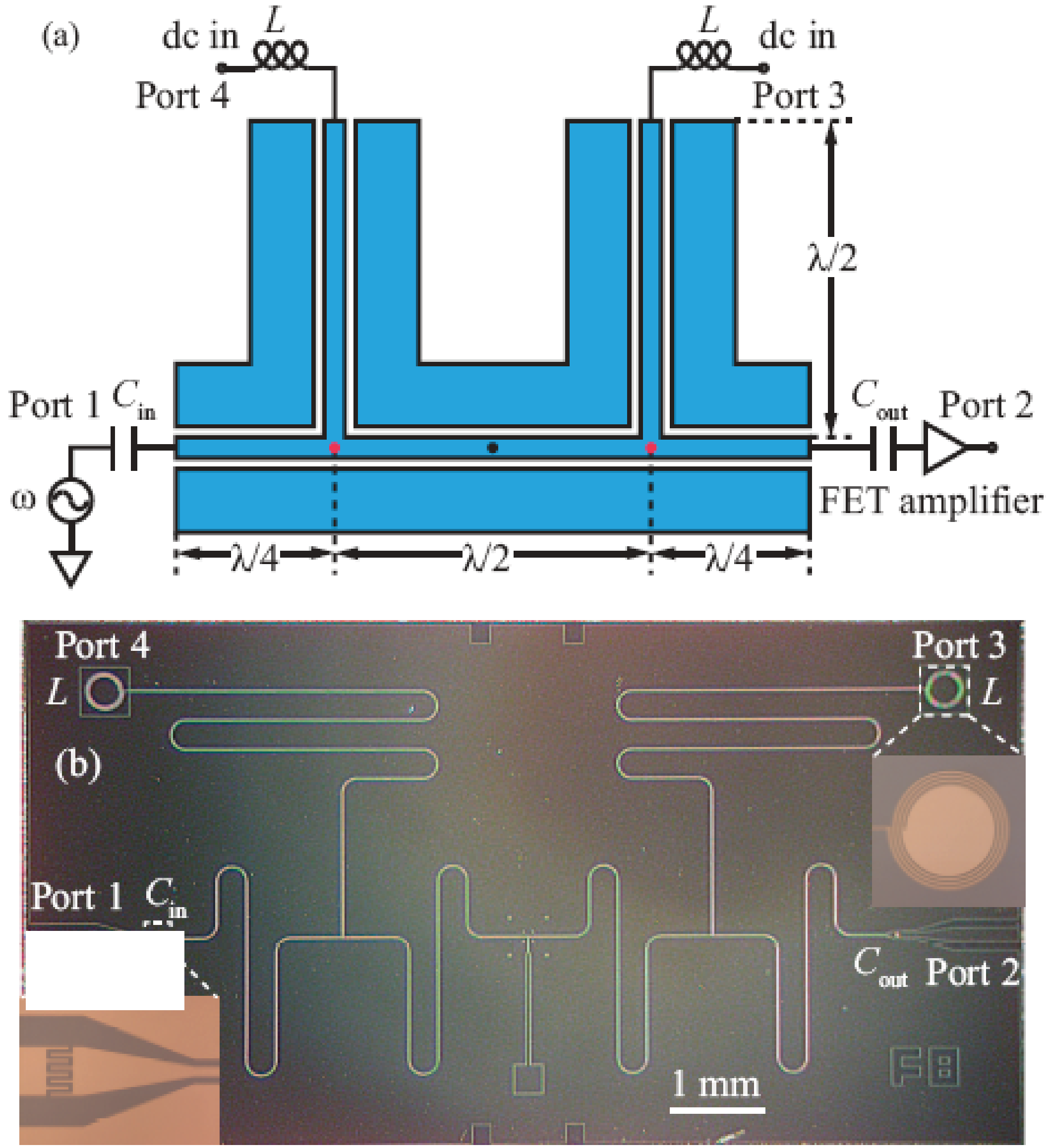
Drive frequency ω_d tuned by varying external dc bias V_{dc} . No external rf drive required (self-oscillating via ac Josephson effect)⇒low noise ⇒macroscopic quantum effects in strongly nonlinear system (?)

$$\omega_d = \frac{L}{L_b}\frac{eV_{dc}}{\hbar}$$

Analysis of classical versus quantum dynamics in progress…

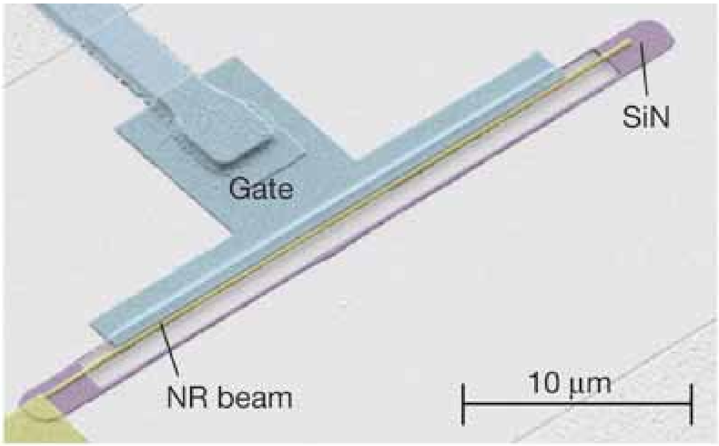
Experiment (in progress)

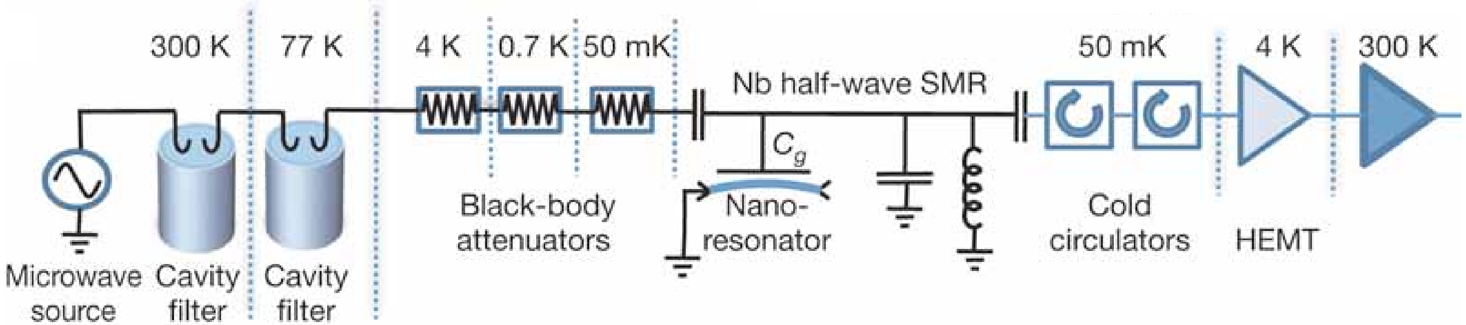
[A. Rimberg *et al*., (2011)]



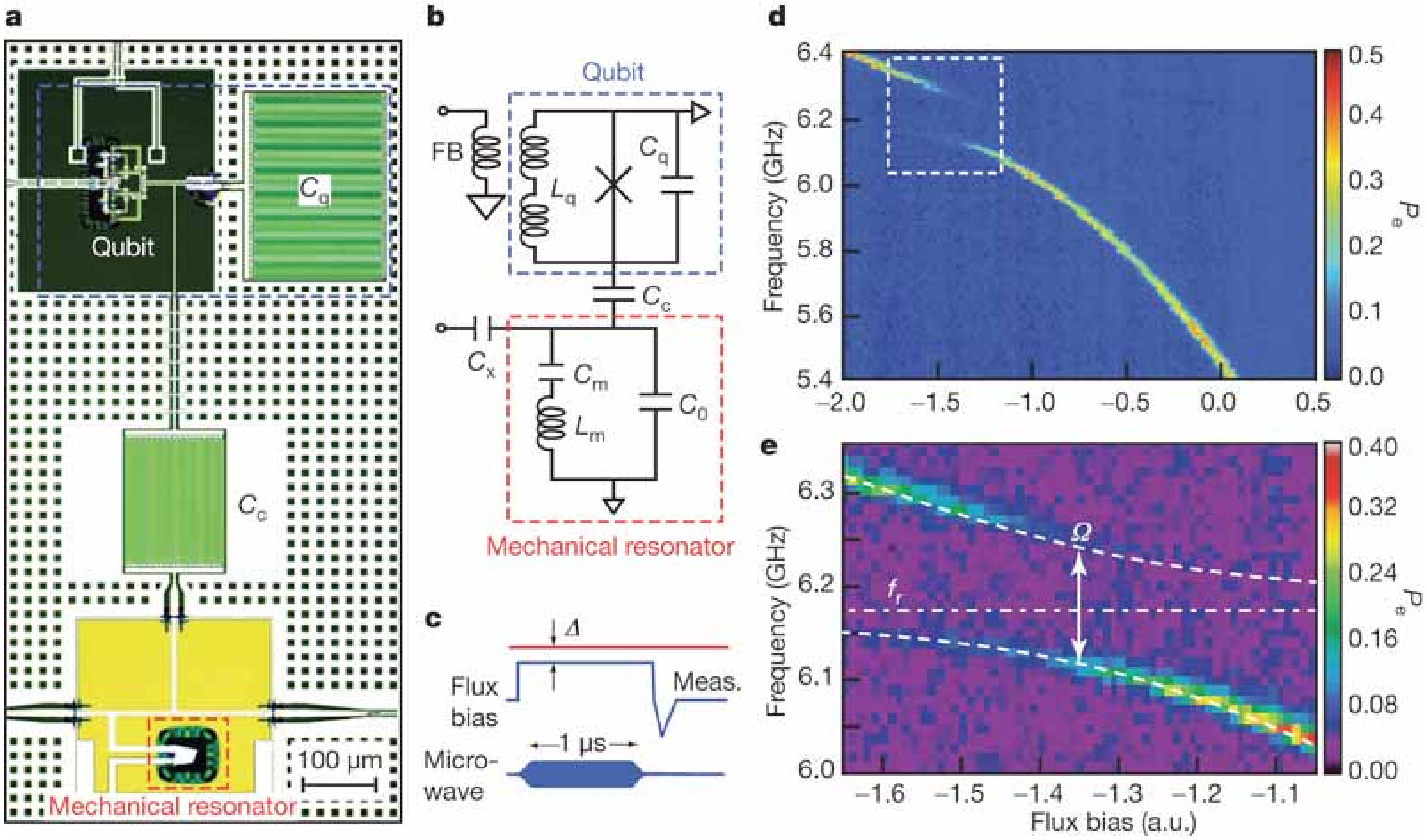
Other cQED-mechanical schemes

- Using driven CPW to cool a mechanical resonator close to its ground state of motion [T. Rocheleau *et al*., *Nature* **463**, 72 (2010)]





•Generation and detection of a mechanical resonator in (quantum) ground, single phonon and superposition states [A. O'Connell *et al*., *Nature* **464**, 697 (2010]



•Strongly coupled cQED-mechanical system [J. Teufel *et al*., *arXiv*:1011.3067 (2010)]